IIa. ACCRETION POWERED PULSARS

The Population

CHAIR: D. Helfand

ACCRETING NEUTRON STARS

N.E. White[1]
EXOSAT Observatory/ESOC
Robert Bosch Str 5
6100 Darmstadt
West Germany

1) Affiliated to the Astrophysics Division of the Space Science Dept of ESA.

ABSTRACT.

This paper reviews accreting neutron stars in X-ray binaries, with particular emphasis on how variations in magnetic field strength may be responsible for explaining the spectral and temporal properties observed from the various systems. This includes a review of X-ray pulsars in both low and high mass systems, and a discussion of the spectral properties of the low mass X-ray binaries.

1. INTRODUCTION

The strength of the magnetic field on the surface of an accreting neutron star in a binary system critically determines the fundemental X-ray properties of that system. If the field is strong then the accretion flow will be disrupted and funnelled onto the magnetic pole and an X-ray pulsar will be seen. If the field is weak (<$5x10^8$ Gauss) and the flow directly interacts with the neutron star surface then X-ray emission will be expected not only from the neutron star, but also from the inner regions of the accretion disk.

The fact that X-ray pulsars are found predominantly in the young OB star systems and not in the older low mass X-ray binaries, LMXRB, is consistent with the view that the magnetic dipole moment of a neutron star decays on a timescale of 10^6 to 10^7 years (Flowers and Ruderman 1977). The radio pulsars with periods between 1 and 10 milli-seconds, some of which have degenerate binary companions, are most probably the remnants of now exhausted low mass X-ray binary systems, LMXRB (see e.g. Alpar et al 1982; Fabian et al 1983; Joss and Rappaport 1983). The measurement of the slow down of these radio pulsars indicates a range of magnetic field strength of $4x10^8$ Gauss to 10^9 Gauss (Taylor 1986). This result raises the possibility that the magnetic field decay timescale increases dramatically when the field has decayed to ~10^9 Gauss and that there may still be a significant field present in many LMXRB (van den Heuvel, van Paradijs and Taam 1986).

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This paper concentrates on how the properties of X-ray pulsars and the spectral properties of LMXRB are influenced by variations in the magnetic dipole field strength. For a discussion of the recent developments arising from the discovery by EXOSAT of quasi-periodic oscillations, QPO, from several of the most luminous LMXRB, the reader is refered to other articles in these proceedings; however some of the conclusions in this review are relevant to models for QPO.

2. THE POPULATIONS

In Figure 1 the galactic distribution of X-ray pulsars is compared with those of the other X-ray sources believed to contain neutron stars. Most of the X-ray pulsars lie along the galactic plane, typical of a population I distribution. The exceptions to this are the sources in the LMC and SMC, X Per (which is only ~300 pc away) and the LMXRB systems Her X-1 and 4U1626-67. The X-ray pulsars within our galaxy with OB star companions have an average distance from the galactic plane of 68 pc, comparable with the scale height of OB stars. The galactic distribution of the non-pulsing LMXRB is more concentrated towards the galactic center with a larger average height above the plane of 540 pc, suggestive of an older population.

The LMXRB come in two flavors. The X-ray burst sources typically have orbital periods of between 40 minutes and 7 hours with X-ray luminosities of $\sim 10^{37}$ erg/s. In addition to these ~30 sources there are 11 high luminosity sources that have luminosities typically a factor of ten larger i.e. close to the Eddington limit for accretion onto a neutron star. Optical studies of the optical counterparts of two of these systems, Cyg X-2 and Sco X-1, have revealed periods of 9 and 0.7 day. The other highly luminous sources lie in the heavily obscured region at the galactic center. The failure to detect X-ray orbital modulations in these systems may be because they have very long orbital periods of order tens of days and/or because of the obscuring effects of an accretion disk corona (White 1986).

The lower luminosity X-ray burst sources are driven by the loss of angular momentum from the binary system causing the orbit to decay forcing the companion to fill its Roche lobe. In the high luminosity systems the reverse occurs with the evolution (expansion) of a gaint companion, driving the components apart (c.f. Webbink, Rappaport and Savonije 1983; Rappaport, Verbunt and Joss 1983). The life time of the former sub-group may be $>10^9$yr, whereas for the latter case it is less, ranges between 10^7 to 10^8 yr.

The OB star pulsing X-ray binaries can also be divided into two sub-groups depending on whether the companion is a super-giant or a Be star (usually class III-V). The supergiant systems have orbital periods from a few days up to 40 days with, in the longer orbital period systems, eccentricities of up to 0.4. In the systems with orbital periods of a few days quasi-Roche lobe overflow may provide a significant fraction of the accretion flow to the neutron star. In the longer orbital period systems stellar wind accretion is sufficient to power the observed X-ray luminosities . The Be star systems tend to have longer orbital periods than their supergiant counterparts, ranging from ~16 day up to several hundred days. Many of these are only seen as transient X-ray pulsars whose outbursts are caused by

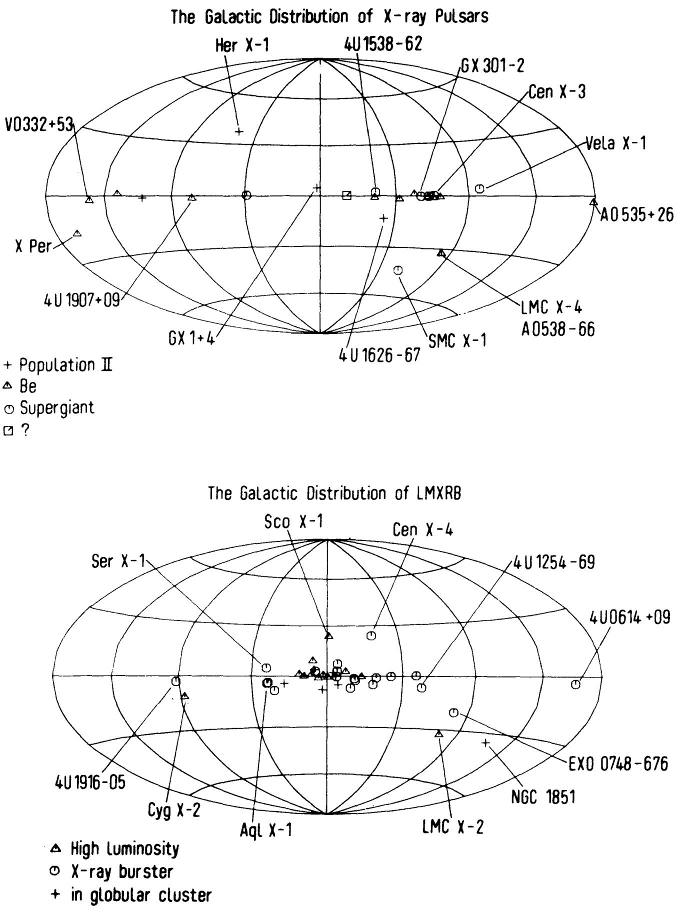

Figure 1. The galactic distribution of X-ray pulsars (top) and low mass X-ray binaries, LMXRB, (bottom). Various sub-populations are indicated by different symbols.

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mass ejection episodes from the companion star (c.f. Stella, White and Rosner 1986 and refs therein).

3. X-RAY PULSARS

There are now 25 confirmed X-ray pulsars with periods ranging from 0.069 to 835 seconds. The pulse period distributions are shown in Figure 2 for the whole group of pulsars and for the various sub-groups outlined above. When all the pulsars are considered there is a possible bi-modal distribution with a clustering around 10 sec and around 200 sec, although its not a strong effect.

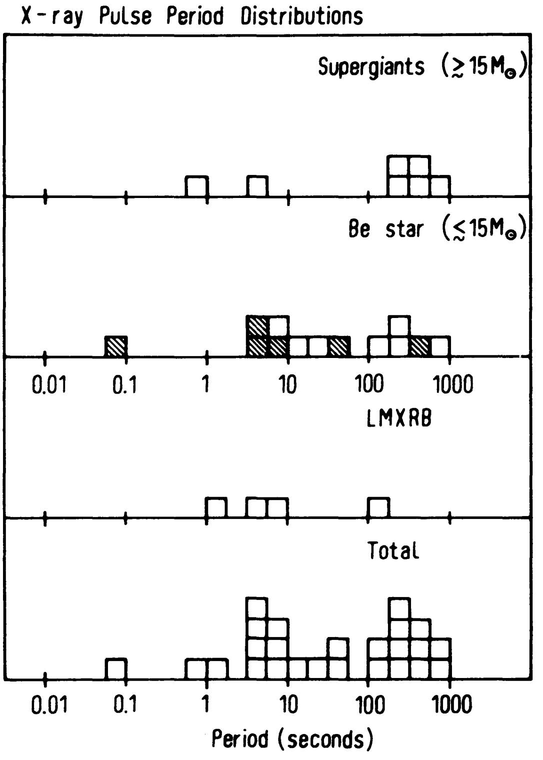

Figure 2. The pulse period distribution of X-ray pulsars. The hatched areas represent transient pulsars in Be star systems.

Looking at the various sub-groups does reveal some possible trends. Three of the pulsars in the LMXRB have periods between 1 and 10 secs, while only one has a period of 100 sec. The reverse trend seems to be the case for the supergiant systems where five out of seven have pulse periods between 100 and 1000 sec. In the Be star systems the

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distribution is much more evenly divided across the period range. The X-ray transient Be star pulsars are marked with shaded boxes. The pulse periods of all but one of the six are less than 100 sec, with one as short as 69 ms.

4. CENTRIFUGAL INHIBITION OF ACCRETION

When a neutron star is born in a binary system it will probably start out spinning rapidly with a period of tens of milli-seconds and then be spun down by various processes to rotate at the periods we now observe (c.f. Henrichs 1983 and refs therein). The spin down process will cease when the rotation period is equal to the Keplerian period at the inner edge of the accretion disk; at periods shorter than this equilibrium value the accretion flow will be centrifugally ejected by centrifugal forces.

In the systems where there is sufficient angular momentum for an accretion disk to form (usually those with Roche lobe overflow) the period is seen to be increasing with a timescale of 100-10,000 yr, depending on the luminosity (c.f. Joss and Rappaport 1984). The spinup timescales are typically much faster than the evolutionary timescale of either the companion or the neutron star magnetic field. This means that the neutron star spin must be re-adjusting to a recent increase in the mass accretion rate. In most of the wind driven systems the pulse periods undergo positive and negative variations in period without any obvious long term trend. In these systems the pulsar is being torqued in random directions by inhomogeneities in the captured stellar wind (Boynton et al 1984).

A centrifugal barrier to accretion will occur when the rotation of the magnetosphere exceeds that of the local Keplerian disk. This sets a lower limit to the X-ray luminosity that can be observed from an accreting neutron star that is given by

$$L_{min}=2x10^{37}.R_x^{-1}.M_x^{-2/3}.\mu_{30}^2.P_s^{-7/3} \text{ erg/s}$$

where R_x, M_x, μ and P_s are the neutron radius, mass, magnetic dipole moment and rotation period in units of 10 km, 1.4 M_o, 10^{30} Gauss/cm^3 and sec. In Figure 3 a plot of luminosity verses pulse period is given for all the pulsars with reasonable distance estimates (from Stella, White and Rosner 1986). Lines of constant μ defined by the above equation are given for various field strengths. An accreting neutron star can only be a bright X-ray source if it lies above one of these lines i.e. the position of a pulsar in this diagram defines a maximum magnetic dipole moment. It is notable that most pulsars lie above the μ=10^{30} Gauss/cm^3 line (corresponding to 10^{12} Gauss).

In plotting Figure 3 the maximum observed luminosity was used because this is the best value documented in the literature. A better restriction on μ comes from using the minimum observed luminosity and

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in Figure 3 the vertical lines indicate the range of luminosity seen from a selection of these objects. In most cases the range is not sufficiently large to change the fact that most of the long period

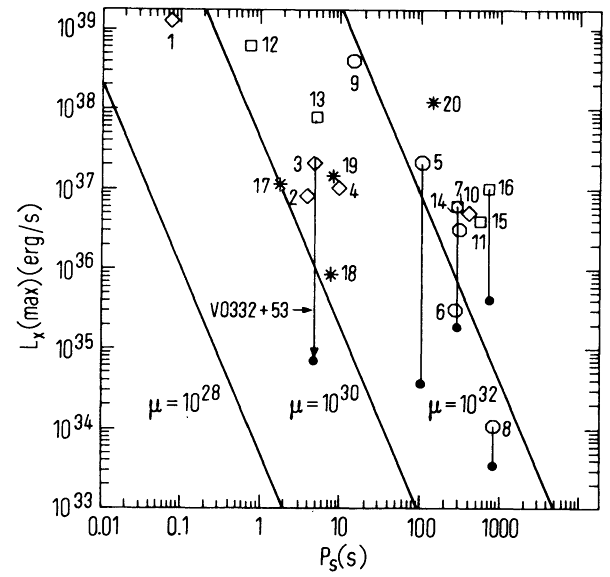

Figure 3. The pulse period vs. maximum luminosity plot for X-ray pulsars. The numbers denote the following sources:

1. A0538-66	12. SMC X-1
2. X0115+63	13. Cen X-3
3. V0332+53	14. Vela X-1
4. X1553-54	15. X1538-52
5. A0535+26	16. X1223-62
6. GX301-2	17. Her X-1
7. X1145-61	18. 1E2259+59
8. X Per	19. X1626-67
9. LMC X-4	20. GX1+4
10. A1118-61	
11. X1145-616	

The diamonds indicate transients, the boxes supergiants, circles Be systems and stars LMXRB.

pulsars lie well above the 10^{12} Gauss line. This means that these systems are either well away from their equilibrium values, or the dipole moments are in excess of 10^{14} Gauss. There is no evidence from radio pulsar spin down measurements that such large dipole fields are common and it seems more likely that the equilibrium period of these long period pulsars was orginally much longer.

Many of the transient X-ray pulsars lie close to the 10^{12} Gauss line and only a small decrease in luminosity will cause the centrifugal barrier to act. The transient nature of these systems is explained by a small increase in mass accretion rate causing the centrifugal barrier to be overcome and the pulsar to suddenly turn on as a bright X-ray pulsar. These Be X-ray transients may represent a large population of dormant systems that are still in the spin down phase, that will in the future become much longer period pulsars.

In 1973 the transient source V0332+53 underwent an exceedingly luminous outburst during which the flux rose smoothly over an interval of a month, then decayed again over the same time interval (Terrell and Priedhorsky 1984). More recently in 1983 a series of mini outbursts with L_{max}/L_{min} >500 were seen which occured every 34 day at the time of periastron passage of the neutron star (Stella et al 1985); no obvious orbital modulation was evident during the 1973 outburst. The overall range of luminosity seen from V0332+53 is indicated in Figure 3. Below the minimum of this range the source was not detected, with an upper limit a factor of 40 below the minimum detected luminosity. The minimum detected luminosity gives an estimate of the dipole field of ~$3.5x10^{11}.d^2$ Gauss, where d is the distance in units of 1.5 kpc. This is quite a low value for the dipole field, although uncertainties in the distance estimate could probably bring it closer to the canonical value. The interesting point about V0332+53 is that the mass loss rate from the companion in 1983/4 was such that the equilibrium point straddled the eccentric orbit, such that only close to perigee was the accretion rate high enough to overcome the centrifugal barrier. This explains why a large orbital modulation of the X-ray flux was seen in 1983/4, but not in 1973 when the mass transfer rate was much larger.

A transient X-ray pulsar where a similarly large X-ray orbital modulation is seen is A0538-66. This source has an exceptionally short spin period of 69 milliseconds and is seen at luminosities that are a factor of ten above the Eddington limit. In order to overcome the centrifugal barrier at all, even at these high accretion rates, a lower than average dipole field strength is required. Taking the minimum observed luminosity observed from this source of ~10^{38} erg/s gives a dipole field of ~10^{11} Gauss. This is a factor of ten below the canonical value.

The position of the LMXRB systems in Figure 3 are also indicated (as * symbols). Her X-1 and 1E2259+586 lie on the 10^{12} Gauss line. For Her X-1 this is somewhat lower than the surface field mesurement obtained from the cyclotron line measurement of $4x10^{12}$ Gauss (Truemper et al 1978). This is probably not inconsistent because the cyclotron measurement reflects the surface field, whereas the centrifugal barrier limit reflects the average field at the magnetospheric boundary; any multi-pole components will tend to make the latter lower.

The binary X-ray pulsar 1E2259+586 is located at the center of the supernova remnant G109.1-1.0 which has an age of ~10^4 years (Gregory and Fahlman 1980). It seems very likely that the remnant is the remains of the supernova which created the X-ray pulsar, which allows the age of the neutron star to established. The faintness of the optical counterpart indicates that this is a LMXRB, with some evidence from X-ray timing and infra-red observations that the orbital period is 38 min (Fahlman and Gregory 1983; Middleditch et al 1983). The observed pulse period of 7 sec is close to the equilibrium period,

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such that if the pulsar was born spinning rapidly it must have been slowed down to its current value in only 10,000 years, which is several orders of magnitude quicker than current spin down theories predict (c.f. Henrichs 1983). Lipunov and Postnov (1985) suggest that this system evolved from an AM Her system where the white dwarf was pushed over the Chandrasekar limit. Scaling, respectively, the ratio of the moment of inertia and radius of a neutron star to that of a white dwarf gives an orginal rotation period and magnetic field strength for the white dwarf projenitor of 100 min and 10^8 Gauss, comparable to the parameters of an AM Her system. The alternate explanantion by van den Heuvel and Bonsema (1984) that this is a post common envelope system does not explain the slow spin of the pulsar.

An AM Her system may also have been the projenitor to the 7 sec X-ray pulsar 4U1626-67, which has a 42 min orbital period (Middleditch et al 1981). The high spinup indicates a readjustment of the pulsar spin to a recent increase in accretion rate (Joss, Avni and Rappaport 1978). For Her X-1 the high magnetic field of the neutron star is incompatable with the expected lifetime of the companion star, unless the neutron star was also formed by white dwarf collapse (Sutantyo et al 1986). The same is probably true for GX1+4 where the companion is a symbiotic star in an orbit of one hundred or more days (Taam and van den Heuvel 1986).

5. SPECTRAL PROPERTIES

While a considerable effort has been made to understand the spectral properties of the X-ray pulsars, it is only comparatively recently

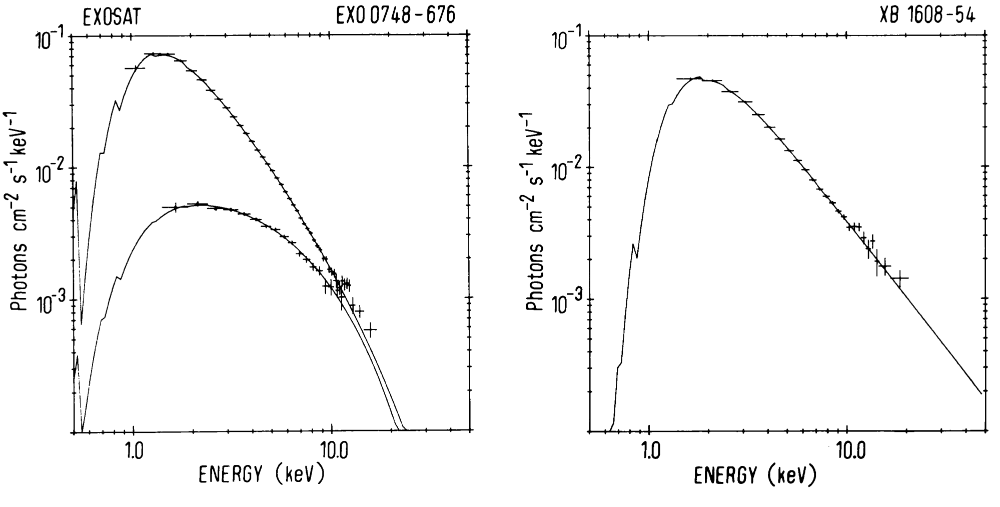

Figure 4. The X-ray spectra from the persistent emission from two typical burst sources. For EXO0748-676 spectra taken at two different intensity levels are shown.

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that any serious attempt has been made to model the spectra of the non-pulsing LMXRB in terms of disk accretion onto a weakly magnetised neutron star. The spectral properties of the X-ray pulsars are quite different from those of the non-pulsing LMXRB. The former typically have a power law spectrum with an energy index of 0 to 1, with a high energy cutoff above 10-20 kev (White, Swank and Holt 1983). The non-pulsing LMXRB spectra are typically softer and can be modelled in two ways depending on whether the luminosity is low or high.

For the X-ray burst sources where the luminosities tend to be lower, the spectra can be modelled by a simple power law that, in some cases, is attenuated at high energies by an exponential cutoff. Two examples of these spectra are shown in Figure 4 taken from EXOSAT observations. The power law energy index is typically of order unity and the high energy exponential cutoff varies from ~5Kev, to not being detectable (>50 Kev). For EXO0748-676 the spectrum changed when the source luminosity declined by a factor 5. In the low state the power law index became considerably less steep with a value of ~0.

In the more luminous Eddington limited LMXRB the spectra can be empirically modelled by the same power law with a high energy exponential cutoff, but with an additional blackbody component. A typical example of this, Cyg X-2, is shown in Figure 5. The blackbody luminosity varies from source to source from ~10% to 50% the total. The temperature is between 1 and 2 kev and the infered radius of a spherical emitter ranges between a few and 10 km. The characteristic Sco X-1 like flaring seen from several of these systems is usually caused by increases in the luminosity of the blackbody component.

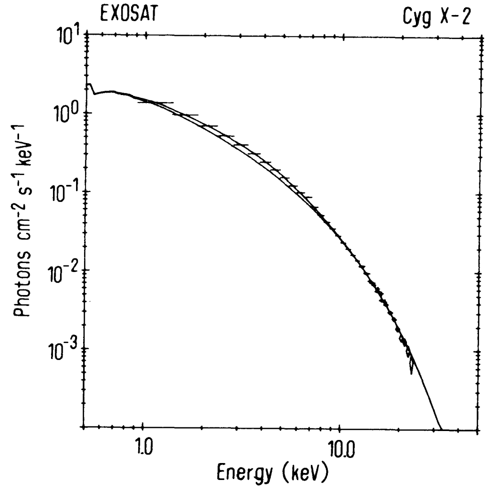

Figure 5. The spectrum of the high luminosity LMXRB Cyg X-2. The lower and upper lines indicate the best fit model with and without the blackbody component.

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equal luminosities to the total, unless the neutron star is rotating close to its limiting break up period. Angular momentum conderations show that only ~0.1 M_o of material is required to spin a neutron star up to its break up rotation period, a number which is attained within only 10^7 years at an accretion rate of 10^{-8} M_o/yr (Alpar et al 1982). The minimum rotation period of a neutron star will be ultimately limited by rotationally induced instabilities causing distortion of the neutron star and the emission of gravitational radiation. The limiting period first estimated by Papaloizou and Pringle (1978) was 1.5 ms, a factor of two longer than break up. This has now been superceded by more recent calculations that indicate that it may be possible to spinup the neutron star much closer to its limiting breakup value (Friedman, Ipser and Parker 1984). For periods less than about twice the break up value the boundary layer luminosity will asymptotically approach zero.

In the inner region of the accretion disk radiation pressure will dominate the disk structure. If the viscous stress tensor scales as the total gas pressure (Shakura and Sunyaev 1973) this inner region is unstable to secular and thermal instabilites and it may swell up into a quasi-optically thin region (Shapiro, Lightman and Eardley 1976). If the stress tensor scales only with the gas pressure then the disk is stable and optically thick (Stella and Rosner 1984). Most of the calculations have assumed that the disk is optically thick up to some inner radius and then becomes optically thin. Most models assume two components, one from the inner disk and another from the boundary layer, with the relative contribution of both as a free parameter.

In modelling Tenma spectra Mitsuda et al (1984) assume that the disk radiates as a blackbody up to an inner radius where it becomes optically thin. The fits to this model give a radius for the optically thin region of two or more neutron star radii and blackbody luminosities comparable to that from the disk. As noted by Lamb (1986) this model predicts enhanced emission from the boundary layer because

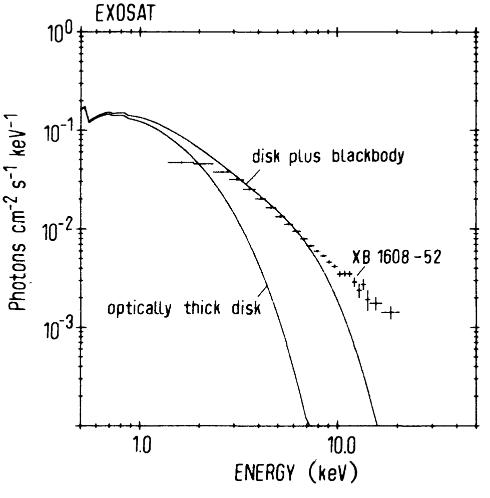

Figure 6. The spectrum of the burst source XB1608-52 fit to the disk model proposed by Mitsuda et al (1984). The two plots represent the model with and without the blackbody emission from the boundary layer.

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the gravitational potential energy from the inner optically thin region must be released at the boundary layer; this is not seen. Another problem is that while reasonable fits can be obtained to the spectra of the bright bulge sources, this model fails to explain the power law spectra of the lower luminosity sources. In Figure 5 the Mitsuda et al model is compared to the spectrum of the persistent emission from the burst source XB1608-52, assuming that the luminosity in the blackbody component is equal to that in the disk. At high energies the observed spectrum does not decay in the manner predicted.

In an alternate model White et al (1986) assume the spectrum from the inner accretion disk is dominated by Comptonization (c.f. Shapiro, Lightman and Eardley 1976). The resulting spectrum in the unsaturated case can be approximated by a power law with an exponential cutoff. The key parameters are the optical depth and temperature of the scattering region and are typically ~10 and 3 kev respectively. Variations in the spectrum like those seen fom the burst source EXO0748-676 are explained in terms of changes in these two parameters. The interesting point is that for many burst sources the inclusion of a blackbody component is not required (>10% the total luminosity) indicating the boundary layer emission to be small i.e. the neutron star rotates close to breakup.

The spectra of the high luminosity systems require a blackbody component at the 10-50% level. This may indicate that in these systems the boundary layer contributes a significant fraction of the luminosity. A more slowly rotating neutron star in these systems may be consistent with the shorter lifetime of these systems expected from evolutionary consierations. The presence of a magnetic field will tend to enhance the blackbody component to more than 50% of the total because the flow of the latter will be interupted by the magnetic field pressure; there is no evidence for such an enhancement in any of these systems.

6. CONCLUSIONS

The overall properties of X-ray pulsars are strongly dependent on how close they spin to the equilibrium point where the centrifugal radius equals the magnetospheric boundary. Most of the long rotation period (>100s) neutron stars lie far from this boundary, unless their surface fields exceed 10^{14} Gauss which seems unlikely. Most of the transient X-ray pulsars in Be star systems do, however, lie close to the critical equilibrium point (when they are in outburst). These sources undergo sharp turn offs during the decline phase when the centrifugal radius moves in side the magnetosphere.

The four (young) X-ray pulsars that are located in the old population of LMXRB most likely resulted from the collapse of an accreting white dwarf. The spectral properties of the remaining LMXRB are dependent on the luminosity (and possibly by the evolutionary history) of the

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system. In both the high and the low luminosity cases the properties can only be explained if part of the emission originates from Comptonization in the inner accretion disk. Optically thick disk models cannot explain the persistent emission from X-ray burst sources. Many of the burst sources do not show evidence for any blackbody component in the persistent flux which may indicate that the neutron stars have been spun up to close to their breakup period (~0.6 milli seconds). The spectra of the high luminosity systems do show evidence for blackbody components, suggesting that the rotation periods may be longer. The spectra provide no evidence for any residual magnetic field on the neutron star as required by some of the QPO models.

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DISCUSSION

W. Lewin: I have two comments: You explained in some detail a model that elegantly explained the transient phenomenon of some systems. There are, however, systems (e.g., A0620-00) for which this scenario is not operative, and for which there are not yet attractive models. Comment 2: In calculating the radius of the magnetosphere you used the dipole field approximation. For small values of this radius (e.g. < 3 stellar radii) the results may not be accurate. Higher order fields can then become important. Therefore, the magnetic dipole field strength for which one finds a magnetospheric radius of ~10 km, using your equation, is probably much higher than the actual value. Fred Lamb mentioned to me once that the dipole field may have to be as low as $\sim 10^7$ G before the disk can touch the surface of the neutron star.

N. White: No comment.

J. Dolan: Certain galactic X-ray binaries with neutron star secondaries (e.g. 4U1700-J7) exhibit nearly circular orbits ($e \approx 0$) but the optical counterpart is not co-rotating. Theory predicts that co-rotation should be established by tidal forces ~10 times faster than the orbit is circularized. If all neutron stars are the result of a SN explosion, then any binary neutron star should be formed with a highly eccentric orbit. Now, co-rotating primaries in X-ray binaries with nearly circular orbits indicate that not all neutron stars are formed in SN explosions, i.e., their orbits have low eccentricity at formation.

S. Kulkarni: First a comment: The X-ray source 1E2259+586 is undoubtedly a low mass binary system now. However, the progenitor system need not necessarily be a low-mass system e.g. Savonige et al. (A&A **155**, 51, 1986) suggest that the initial configuration for 1E2259+586 consists of a 5 $M_\odot$ and 8 $M_\odot$ binary. If their scenario is correct it may be inappropriate to classify 1E2259+586 and perhaps 4U1626-67 as low-mass X-ray pulsars. Now a question: I notice that you quote a $Z_{rms} \sim 580$ pc for all LMXB. The Z_{rms} for the 8 bright, bulge X-ray sources is only $\lesssim 300$ pc. Are we being fooled by small number statistics or are there two classes of sources?

N. White: The scale height maybe different for the bright bulge sources, but with only eight sources we are dealing with small numbers and the uncertainties are difficult to estimate.

J. Grindlay: I would like to make two brief comments: 1) Concerning your discussion of theoretical models for X-ray spectra, I would like to draw attention to work by (Czerny, Czerny and Grindlay 1986) which predicts the emission from the disk vs. boundary layer components which actually fit the data for burst sources. 2) In regard to Kulkarni's question, one should keep in mind that the brightest bulge sources may have had a different evolutionary origin than the lower luminosity systems such as bursters and globular cluster sources. It is unfortunate that there are not more of the bright luminosity galactic bulge sources to better determine their scale height to test whether it is indeed smaller than for the bursters.

V. Trimble: Recent models of rapidly rotating neutron stars indicate that for most reasonable equations of state, the m=2 and m=3 (gravitational radiation) modes are not exited before you reach break up (rotational KE > gravitational BE). Presumably this doesn't affect the evolution much since spin up still has to stop near 1 msec.

N. White: It is very relevant. If the neutron star rotates close to break up then the energy released in the boundary layer will be small. This would be consistent with the fact that we do not detect blackbody components > 10% of the total luminosity in the X-ray burst sources and would suggest that they have been completely spun up.

E. van den Heuvel: The B-star in A0538-66 has a mass of about 8 or 9 solar masses according to the work of Hutchings et al., and is, according to its spectral type at quiescence, already evolved away from the main sequence (luminosity class III). This indicates an age $\gtrsim$ 15 million years for the neutron star. Also, the magnetic field may be larger than the 3×10^{10} G you mention. If I take the period to be the equilibrium period corresponding to maximum X-ray luminosity, of > 10^{39} ergs, I get B ~ 3×10^{11} G. Taking this together with the age of 15 million years, it could still have been born with a strong field $\gtrsim 10^{12}$ G.

N. White: You are correct about the magnetic field, there was a transcription error on my viewgraph. This is still rather low however. With regard to the evolution timescale we need a good estimate of the eccentricity first to see if the circularization timescale is consistent with the model.

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